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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : H01H 47/32 | A1

(11) International Publication Number: WO 93/07637

(43) International Publication Date: 15 April 1993 (15.04.93)

(21) International Application Number: PCT/CA92/00454

(22) International Filing Date: 7 October 1992 (07.10.92)

(30) Priority data:
2,053,540 11 October 1991 (11.10.91) CA

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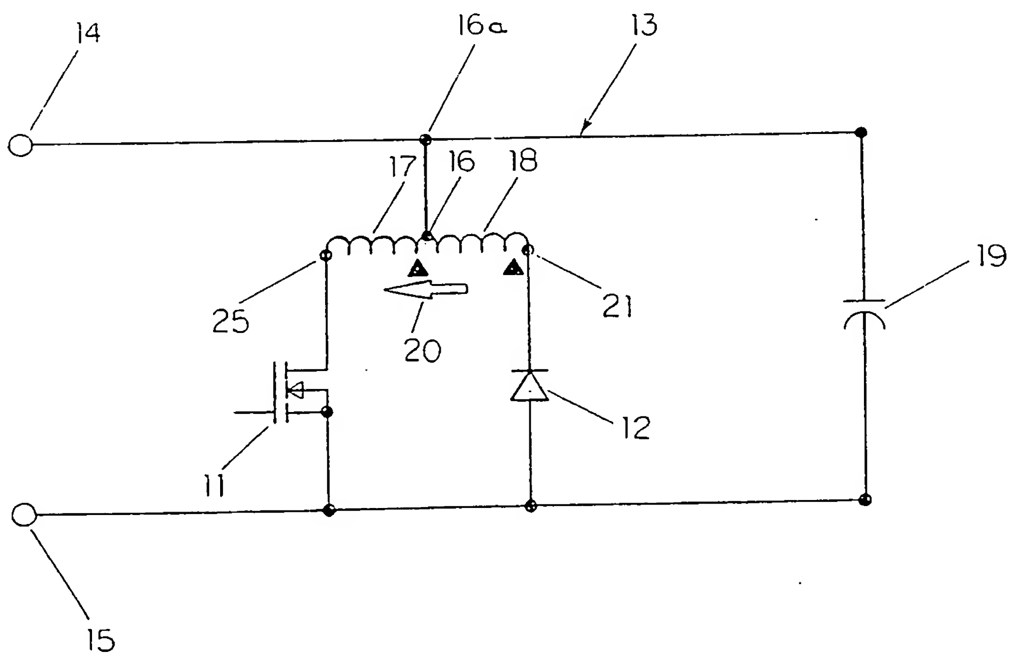
(81) Designated States: AT, AU, BR, DE, FI, GB, HU, JP, KP, KR, NL, RU, SE, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, SE).

Published
With international search report.

(54) Title: INDUCTIVE LOAD SWITCH UTILIZING SIMPLIFIED GATING



(57) Abstract

The design of an electronic switch suitable for regulating the current supplied to inductive loads, such as magnetic bearing is disclosed. The electronic switch employs an alternate circuit design which differs from the conventional "H-Bridge" arrangement. The electronic switch is characterized by utilizing only one semiconductor switch and one rectifying element means. Th novel circuit of the electronic switch reduces the complexity of the switch compared to the conventional "H-Bridge" arrangement

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Inductive Load Switch Utilizing Simplified Gating

TECHNICAL FIELD

The present invention relates to a simplified electronic switch suitable for modulating the current supplied to an inductive load.

BACKGROUND ART

Electronic switches for regulating the current supplied to inductive loads are well known electronic devices. In the case of electromagnetic bearings the electronic switch is connected to the coil of the electromagnet. In operation the electronic switch regulates the amount of current supplied to the coil of the electromagnet in response to a control signal. The force delivered by the magnetic bearing is related to the amount of current supplied to the coil of the electromagnet. By providing an electronic switch capable of modulating the current supplied to the coil of the electromagnet, it is possible to modulate the force delivered by the magnetic bearing. Such magnetic bearings are well known and are described in further detain in, for example United States Patent No. 4500142.

Electronic switches are typically of an "H-Bridge" design. The "H-Bridge" design consists of two semiconductor switches and two rectifying elements arranged to form an "H" shape. The semiconductor switches are commonly of the N-channel Field Effect Transistor (FET) type. A FET has three terminals commonly called the drain terminal, the source terminal and the gate terminal. When the FET is turned on, current flows from the source terminal to the drain terminal. To turn the FET on, a control signal at a voltage higher than the voltage at the source terminal must be applied to the gate terminal. When the switch is connected to an inductive load in the "H-Bridge" arrangement, the source voltage applied to one of the semiconductor switches varies as the voltage across the inductive load varies. The gate control signal, whose reference is the source of the FET must therefore swing with the load voltage. This swing may be hundreds of volts in some applications. Commonly, an isolation scheme is used and this entails complicated and expensive circuitry. In cases where very fast switching is necessary, additional subtle problems increase the design and manufacturing costs. This extra circuit adds to the complexity and cost of the H-Bridge switch. Although conventional H-Bridge switches are suitable for certain

applications, the complexity of the switch and the number of expensive electronic ...ents comprising the electronic switch results in an unacceptably high cost for ...y applications.

Furthermore, because only one rectifying element means and one semiconductor switch means are preferably employed, the preferred electronic switching means of this invention has a lower power loss than that of a conventional H-bridge.

It is, therefore, the object of the present invention to provide a simplified electronic switch arrangement suitable for use with inductive loads.

DISCLOSURE OF THE INVENTION

Accordingly there is provided an electronic switch suitable for modulating the current supplied to an inductive load comprising:

(1) a semiconductor switch means;

(2) a rectifying element means;

(3) an inductive load that contains a first inductive load section and a second inductive load section;

(4) an intermediate connection between said first inductive load section and said second inductive load section; and

(5) a first power supply terminal and a second power supply terminal wherein;

- (a) said semiconductor switch means is connected between said first power supply terminal and said first inductive load section,
- (b) said rectifying element means is connected between said first power supply terminal and said second inductive load section,
- (c) said first inductive load section is connected to said semiconductor switch means and to said second power supply terminal, between said semiconductor switch means and said second power supply terminal,
- (d) said second inductive load section is connected to said rectifying element means and to said second power supply terminal, between said rectifying element means and said second power supply terminal,
- (e) said first inductive load section and said second inductive load section are connected to said intermediate connection such that the polarity of

said first inductive load section is the opposite of the polarity of said second inductive load section at said intermediate connection.

Preferably the semiconductor switch means is a Field Effect Transistor, therefore, minimizing the losses inherent to semiconductor switches. As a further preference the rectifying element means is a Diode.

BRIEF DESCRIPTION OF DRAWINGS

The embodiment of the present invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a schematic diagram of a conventional "H-Bridge" switch and,

Figure 2 is a schematic diagram of the simplified electronic switch arrangement according to this invention, and

Figure 3 is a schematic diagram of an alternate embodiment of the simplified electronic switch according to this invention.

Referring to Figure 1, a brief description of the "H-Bridge" switch serves to describe a typical arrangement and operation of the conventional electronic switch when connected to an inductive load. Switch 1 is comprised of two electronic switch means shown as Field Effect Transistors (FETs) 2 and 3, and two rectifying element means shown as Diodes 4 and 5 and a capacitor 6. The drain terminal of FET 2 is connected to high potential terminal 8 of a direct current power supply such as a battery (not shown). Diode 5 has its cathode connected to the source terminal of FET 2. The anode of Diode 5 is connected to the low potential terminal 9 of the power supply. Diode 5 and FET 2 defines the first FET, Diode series branch. Similarly, Diode 4 and FET 3 are connected in series, however in this case, the anode of Diode 4 is connected to the high potential terminal of the power supply and the source terminal of FET 3 is connected to the low potential terminal of the power supply. A further connection between the drain of FET 3 and the cathode of Diode 4 completes the second FET, Diode series branch. One end of inductive load 7 is connected to the first FET, Diode series branch between Diode 5 and FET 2. The second end of the inductive load is connected to the second FET, Diode series branch between FET 3 and Diode 4.

During operation, the simultaneous application of gate signals to the gate terminals of FETs 2 and 3 causes each FET to begin conducting, thereby connecting inductive load 7 across the terminals of the power supply. A current begins to flow through the load in the direction indicated by arrow 10 and increases with time according to $\mathbf{E} = \mathbf{L}\,\frac{\mathbf{dI}}{\mathbf{dT}}$, wherein **E** is equal to the power supply voltage, **L** is inductance and $\frac{\mathbf{dI}}{\mathbf{dT}}$ is the derivative of **I** (inductance) with respect to **T** (time).

Once the gating signals are removed from FETs 2 and 3, current flow between the terminals of the power supply through the inductive load ceases. A potential with reversed polarity appears across inductive load 7. This voltage causes Diodes 4 and 5 to become forward biased and begin conducting current out of the inductor.

Current exiting from the load through the Diodes charges capacitor 6 which is connected across the terminals of the power supply. When gating signals are subsequently applied to FETs 2 and 3, energy stored in the capacitor during discharging of the inductive load is transferred back into the inductive load through FETs 2 and 3.

If, during operation, the length of time that the gating signals are applied to the FETs equals the length of time that signals are not applied to the gate terminals of the FETs, the electronic switch is said to have a duty cycle of 50%. In this situation the average current level in the inductor remains constant. If the gating signals are applied to the gate terminals of the FETs for more than half the time the electronic switch has a duty cycle of more than 50%. If the duty cycle is more than 50%, the inductor is connected across the terminals of the power supply more than half the time. The result is the inductor is being charged for a longer time then it is being discharged and the average current through the inductor increases. The reverse is true when the duty cycle is less than 50%. The electronic switches conduct for less than half the time, and therefore, inductor discharges for a longer time than it charges resulting in a decrease in the average current through the inductor.

For a FET to conduct current between its source and drain terminals, the gate signal must be at a higher voltage then the source terminal voltage. In the H-Bridge

electronic switch shown on Figure 1, the voltage appearing at the source terminal of FET 2 varies due to the charging and discharging of inductive load 7. To ensure that FET 2 does not turn off prematurely, due to the source voltage being greater than the gate voltage, a level shift circuit is commonly used. The level shaft circuit adds complexity to the design and increases the cost of the switch. Such level shift circuits are well known and are described in further detail in, for example, the technical paper, Power Drives Linking Brains to Braun published in the October 13, 1988 edition of Electronic Design Magazine.

Turning now to the present invention shown on Figure 2, switch 13 contains one semiconductor switch means shown here as FET 11 and one rectifying element means shown here as Diode 12. The inductive load connected to the electronic switch is comprised of inductive load section 17 and inductive load section 18. Inductive sections 17 and 18 have a common connection (connection 16) to the high potential terminal 14 of a direct current power supply (not shown). The positive end of the windings of inductive sections 17 and 18 are indicated on Figure 2 by triangles. Thus, the polarity of the two inductive load sections 17 and 18 must be the opposite of one another at intermediate connection 16a. Stated alternatively, the polarity of the inductive load sections 17 and 18 is the same at the points indicated by the triangles of Figure 2. (As an aside, it should be noted that the inductive load sections 17 and 18 may, in an alternate embodiment, be physically separate from one another. In this alternate embodiment, each of inductive load sections 17 and 18 may be connected by separate connecting wires to intermediate connection 16a). Between the low potential terminal of the power supply 15 and the high potential terminal of the power supply 14 capacitor 19 is connected. The source terminal of FET 11 is connected to the low potential terminal 15 of the power supply. The drain terminal of FET 11 is connected to end terminal 25 of inductive load section 17. The anode of Diode 12 is connected to the low potential terminal 15 of the power supply and the cathode of Diode 12 is connected to end terminal 21 of inductive load section 18.

During operation of the electronic switch, a gating signal is applied to the gate terminal of FET 11. This causes the FET to begin conducting and results in inductive load section 17 being connected across terminals 14 and 15 of the power supply. A

current begins to flow through inductive load section 17 in the direction indicated by arrow 20. The current through inductive load section 17 increases according to the previously described equation:

$$\mathbf{E} = \mathbf{L}\,\frac{\mathbf{dI}}{\mathbf{dT}}$$

wherein **E** is equal to the power supply voltage, **I** is equal to the current and **L** equals the inductance of inductive load section 17.

When the gating signal is removed from FET 11, current flow between the terminals of the power supply through inductive load section 17 ceases. Since inductive load sections 17 and 18 are part of one inductive load, the two sections are magnetically coupled. The opening of the current path through inductive load section 17 causes the polarity across both inductive load sections 17 and 18 to reverse. With the reversed polarity of inductive load section 18, Diode 12 becomes forward biased and allows the charge stored in the inductive load to discharge into capacitor 19. When a subsequent gating signal is applied to FET 11, energy stored in the capacitor during discharging of the inductive load section 18 is transferred into inductive load section 17.

The average current level in the inductive load comprised of inductor sections 17 and 18 is controlled in the same manner as with the conventional H-Bridge switch previously described. A gate signal duty cycle of 50% results in a steady average current through the inductive load. A duty cycle of more this 50% allows the inductive load more time to charge then to discharge and results in an increasing average current value through the inductive load. A duty cycle of less than 50% allows for more discharging time than charging time and the average current through the inductive load decreases.

Figure 3 shows an alternate embodiment of the electronic switch. In this embodiment, the semiconductor switch means is comprised of a plurality of FETs 22 and the rectifying element means is comprised of a plurality of Diodes 23. If a single FET is not capable of conducting the large currents required, a plurality of FETs may be arranged in parallel. The gating signal would be applied simultaneously to the gate terminal of all the FETs. The current charging the inductive load section would be divided amongst the FETs.

Similarly, if a single rectifying element was unable to carry the large currents flowing out of the inductive load, a plurality of Diodes may be arranged in parallel. The current flow through each Diode would then be reduced.

When used to regulate the current through the winding of an electromagnetic bearing, inductive load sectors 17 and 18 are formed as the coil of the electromagnet. Between the ends of the coil, terminal 16a is provided to form an intermediate connection between the power supply terminal and the coil. The intermediate connection formed by terminal 16 may be constructed by various methods. The coil for the electromagnet may be first wound and then a separate wire may be soldered on to one of the turns of wire forming the coil. An alternative method of forming the inductive load sections would be to wind two separate coils from wire and then connect one end of each coil to the same terminal of the power supply.

Although the present switch has been described as incorporating FETs, it should be apparent to those skilled in the art that other semiconductor switches such as bipolar junction transistors and the like may be used in place of the FETs to form the semiconductor switch means. Similarly the present switch has been described as incorporating a Diodes as the rectifying elements forming the required rectifying element means. It should be apparent that an alternative to Diodes may be used to form the rectifying element means. An alternative to the Diode could be, for example a transistor switch arrangement. When the transistor switch arrangement is used in place of the Diodes, an appropriate gating signal would be applied to the transistor switch to allow current to flow between inductive load section 18 and capacitor 19, and therefore allow the discharge of inductive load section 18.

It should further be apparent to those skilled in the art that modification and variations may be made to the present invention without departing from the scope of the present invention as defined by the appended claims.

INDUSTRIAL APPLICABILITY

The present switch is generally suitable for regulating the current supplied to an inductive load. The switch is especially suitable for use in a magnetic bearing.

CLAIMS

1. An electronic switch suitable for modulating the current supplied to an inductive load comprising:

(1) a semiconductor switch means;

(2) a rectifying element means;

(3) an inductive load that contains a first inductive load section and a second inductive load section;

(4) an intermediate connection between said first inductive load section and said second inductive load section; and

(5) a first power supply terminal and a second power supply terminal wherein;

  (a) said semiconductor switch means is connected between said first power supply terminal and said first inductive load section,

  (b) said rectifying element means is connected between said first power supply terminal and said second inductive load section,

  (c) said first inductive load section is connected to said semiconductor switch means and to said second power supply terminal, between said semiconductor switch means and said second power supply terminal,

  (d) said second inductive load section is connected to said rectifying element means and to said second power supply terminal, between said rectifying element means and said second power supply terminal,

  (e) said first inductive load section and said second inductive load section are connected to said intermediate connection such that the polarity of said first inductive load section is the opposite of the polarity of said second inductive load section at said intermediate connection.

2. The electronic switch according to claim 1, wherein said first inductive load section and said second inductive load section are formed as a coil.

3. The electronic switch according to claim 2, wherein said coil forms part of an electromagnet.

4. The electronic switch according to claim 1, wherein said inductive load is a magnetic bearing.

5. The electronic switch according to claim 2, wherein said first inductive load section and said second inductive load section are defined by a connection between said coil and said second power supply terminal.

6. The electronic switch according to claim 2 wherein:
   (a) said first inductive load section is formed as a first discrete coil having one end of said first discrete coil connected to said second power supply terminal and,
   (b) said second inductive load section is formed as a second discrete coil having one end of said second discrete coil connected to said second power supply terminal.

7. The electronic switch according to claim 2, wherein approximately half of the turns of said coil form said first inductive load section.

8. The electronic switch according to claim 1, wherein said first power supply terminal is the low potential terminal.

9. The electronic switch according to claim 1, wherein said second power supply terminal is the high potential terminal.

10. The electronic switch according to claim 1, wherein said semiconductor switch means consists of a Field Effect Transistor.

11. The electronic switch according to claim 1, wherein said rectifying element means consists of a Diode.

12. The electronic switch according to claim 1, wherein said semiconductor switch means consists of a plurality of semiconductor switches.

13. The electronic switch according to claim 1, wherein said rectifying element means consists of a plurality of rectifying elements.

14. The electronic switch according to claim 9, wherein said plurality of semiconductor switches is a plurality of Field Effect Transisters.

15. The electronic switch according to claim 10, wherein said plurality of rectifying elements is a plurality of Diodes.

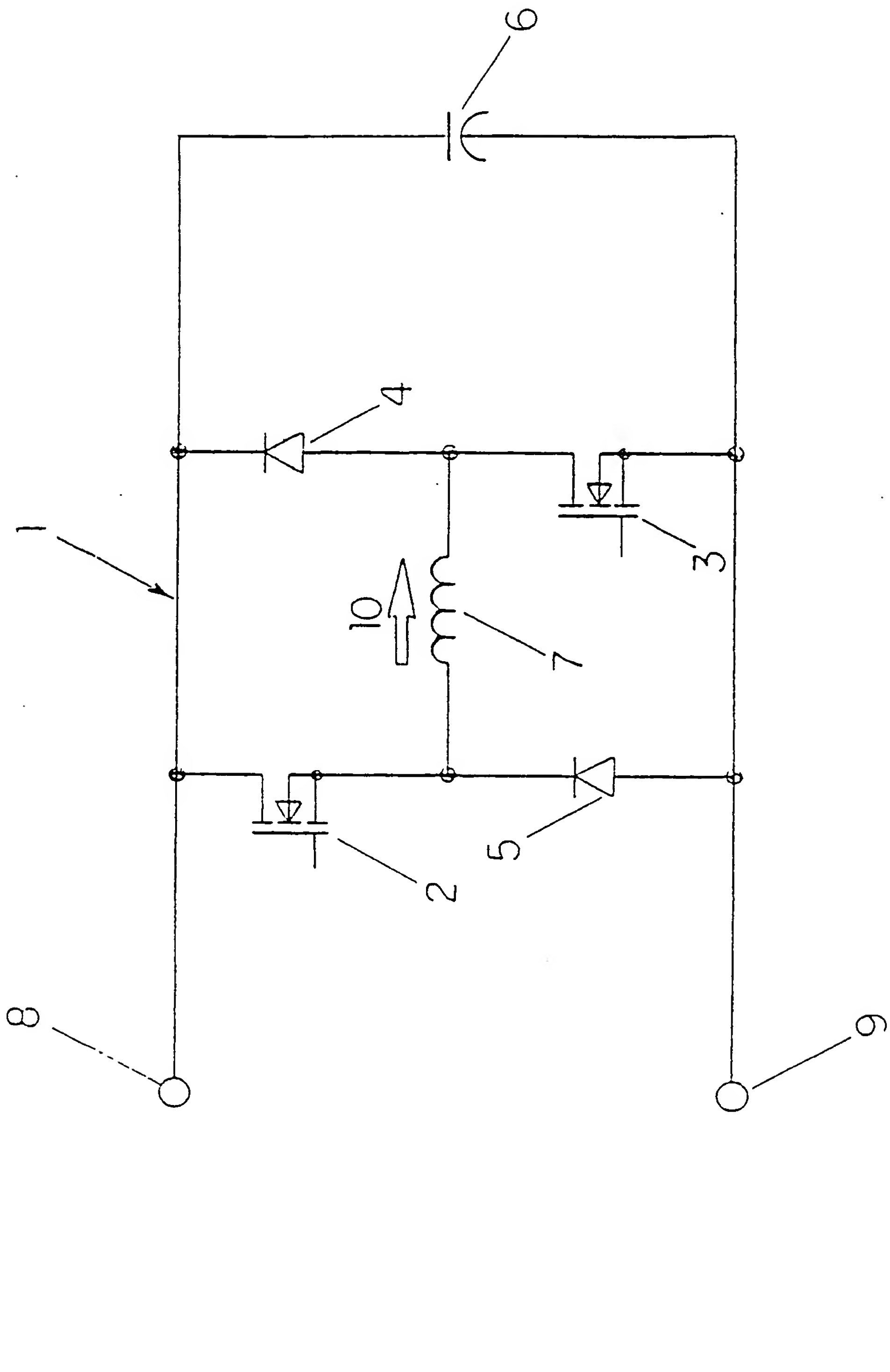

FIGURE 1
(PRIOR ART)

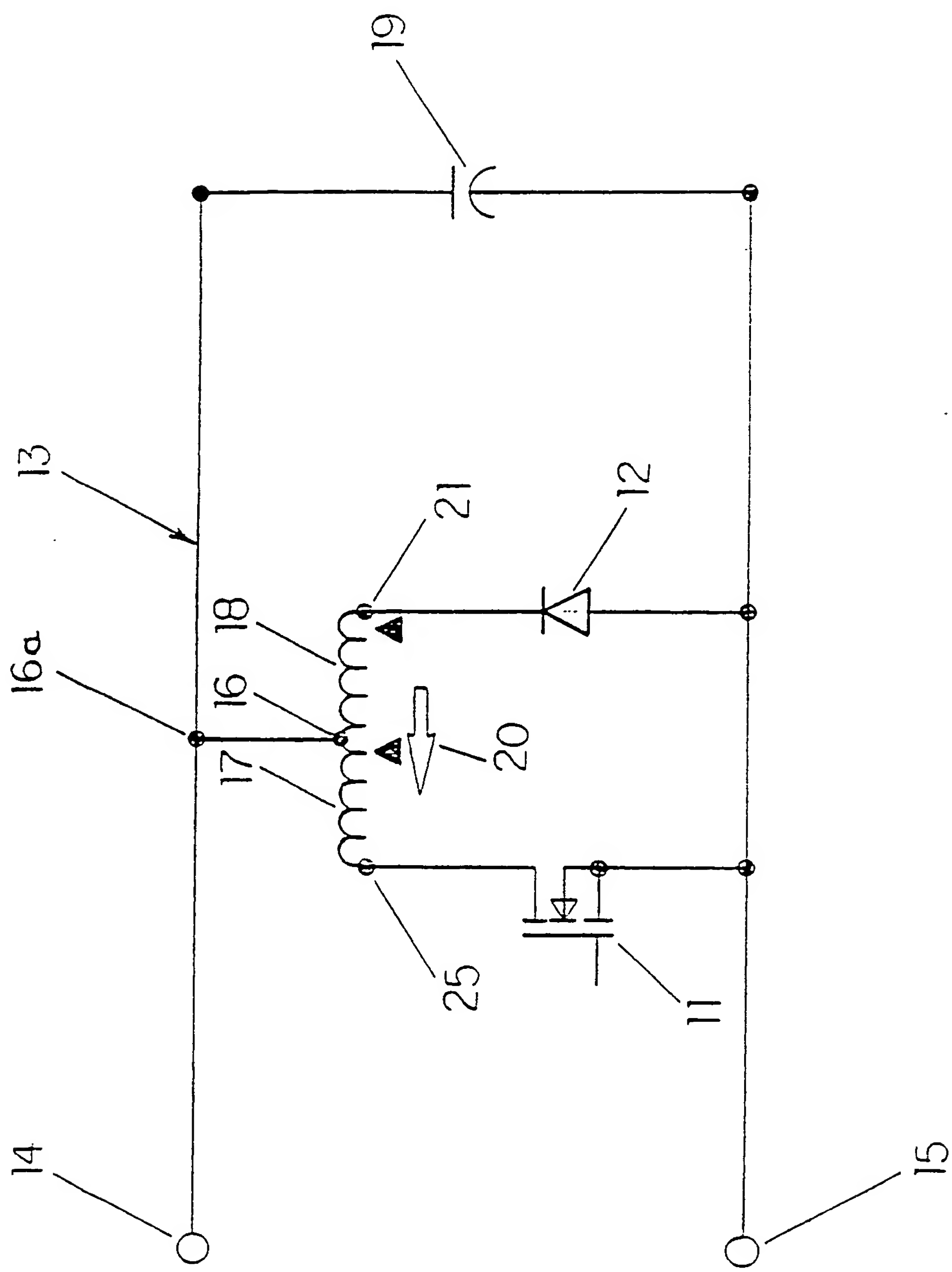

FIGURE 2

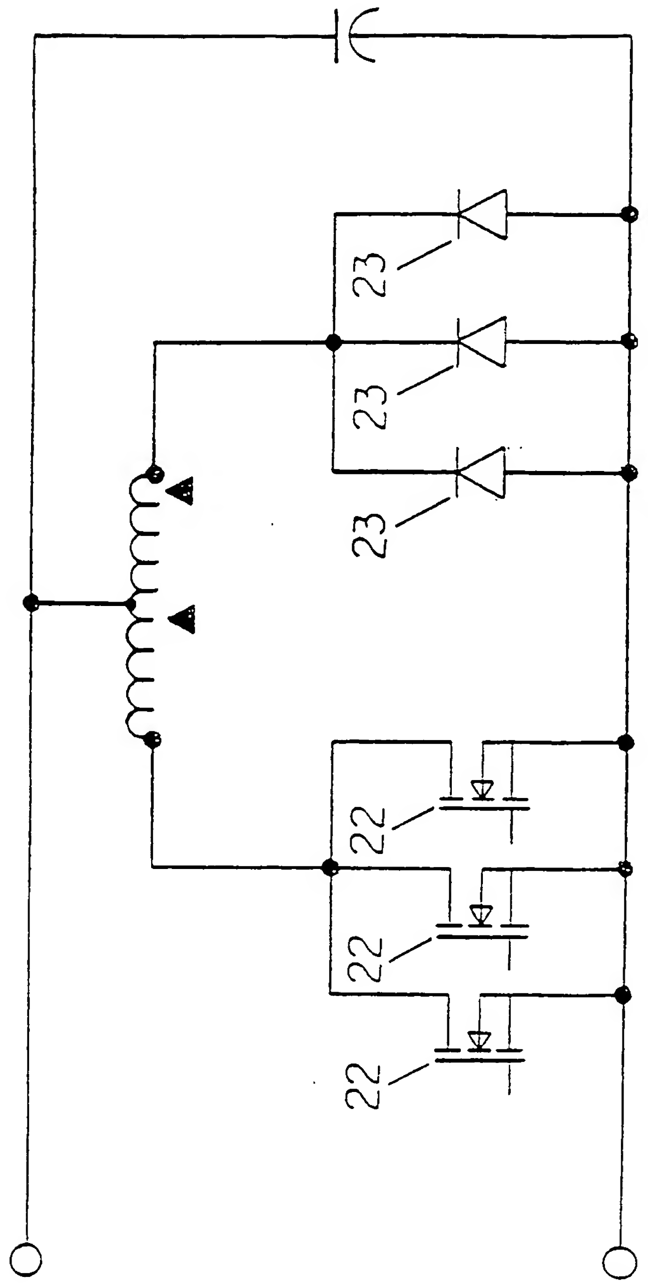

FIGURE 3

INTERNATIONAL SEARCH REPORT

International Application No PCT/CA 92/00454

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H01H47/32

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01H ; H03K

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
X	DE,A,1 922 955 (ULLRICH) 19 November 1970 see page 5, paragraph 2; claim 1; figure 2 ---	1-15
A	DE,A,2 026 434 (SIEMENS) 9 December 1971 see page 3, paragraph 3; figure ---	1,2
A	US,A,4 890 188 (RUSSELL) 26 December 1989 see figure 5 -----	1

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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1 **IV. CERTIFICATION**

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
16 DECEMBER 1992	22. 12. 92
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	SALM R.

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. CA 9200454 SA 65455

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 16/12/92
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE-A-1922955	19-11-70	None	
DE-A-2026434	09-12-71	None	
US-A-4890188	26-12-89	JP-A- 2162705	22-06-90